Submesoscale Routes to Lateral Mixing in the Ocean

Amit Tandon
Physics Department, UMass Dartmouth
285 Old Westport Rd
North Dartmouth MA 02747
Phone: (508) 999-8357 fax: (508) 999-9115 email: atandon@umassd.edu

Grant Number: N00014-09-1-0196

Amala Mahadevan
Department of Earth Sciences
Boston University
675 Commonwealth Avenue
Boston, MA 02215
Phone: (617) 353 5511 fax (617) 353 3290 email: amala@bu.edu

Grant Number: N000140910179
http://varun.bu.edu/latmix

LONG-TERM GOALS

To determine whether lateral mixing at O(1-10 km) scales is due to a balanced or unbalanced downscale cascade from the mesoscale, or due to local vertical mixing by internal waves and surface forcing.

OBJECTIVES

Our work will test hypothesis 3 of the white paper "Scalable Lateral Mixing and Coherent Turbulence": Non-QG, submesoscale instabilities feed a forward cascade of energy, scalar and Ertel PV variance, which enhances both isopycnal and diapycnal mixing. Related hypotheses are that submesoscale variability is associated with coherent structures and anisotropic mixing. Further, submesoscale processes are inherently vertical, as well as horizontal, and that submesoscale processes facilitate cross-front exchange.

APPROACH

Our approach is to run a number of process studies using a three-dimensional non-hydrostatic model written by Amala Mahadevan (PI from Boston University *e.g.* Mahadevan and Tandon 2006). The typical model resolution for resolving submesoscales is about 1 km in the horizontal. We examined processes in a domain approximately 100 km x 200 km, but recently, we have improved the model to run on much larger domains (approximately 500 km x 1000 km) at the same horizontal resolution.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **Submesoscale Routes to Lateral Mixing in the Ocean**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Massachusetts Dartmouth,Physics Department,285 Old Westport Rd,North Dartmouth,MA,02747**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

The three-dimensional non-hydrostatic submesoscale resolving model has been optimized and scaled up for use on modern multi-core computer architecture, achieving an efficiency that allows modeling larger domains with meso- and submeso-scale interaction at high resolution.

An initial set of numerical simulations have been carried out for a baroclinically unstable front in a periodic channel,forced by a constant surface wind stress in many cases. We have analyzed the skew and residual components of across-front buoyancy fluxes and the along-isopycnal bolus transport driven by sub-mesoscale eddies .

Pre-observational process studies have been carried out with characteristic values of stratification, mixed layer depth, and lateral buoyancy gradients provided by ONR LATMIX PIs Jim Ledwell and Miles Sundermeyer in accordance with observations from the site with weak frontal gradients.

We have analyzed numerical experiments in which dye dispersion is examined for the submesoscale frontal instabilities in the presence of wind. The dye is released at two depths in zonal streaks at the beginning of the simulation. The variance in dye concentration is analyzed in time along isopycnal surfaces to study lateral mixing of the dye at various isopycnal depths as a function of mixed layer depth and lateral buoyancy gradient.

RESULTS

In simulations without wind stress, the front restratifies due to mixed layer eddies, as expected from previous work (Fox-Kemper *et al.* 2008, Thomas *et al.* 2008). This restratification can be opposed by a downfront wind stress (acting in the direction of the geostrophic velocity) that drives a surface Ekman flow from the dense to the light side of the front and arrests the slumping of isopycnals. A scaling diagnostic is suggested to determine whether the effect of eddies or wind dominates under different conditions. Though the cross-front transport of buoyancy induced by the downfront component of the wind opposes restratification by mixed layer eddies, it becomes diminished as the growth of the frontal instability and eddies disrupt alignment between the wind and frontal axis.

A new capability of our work with Raffaele Ferrari, is the application of Transformed Eulerian Mean framework in a situation where the vertical buoyancy gradient in the mixed layer is very small. By re-defining and estimating the eddy induced overturning streamfunction in the mixed layer, we separate the along- and cross-isopycnal fluxes of buoyancy associated with submesoscale mixed layer eddies and demonstrate the need for parameterization of the advective, along-isopycnal flux. An article describing this work is to appear in the Journal of Geophysical Research.

In the initial dye experiments, the dye stretches and folds in streaky filaments, At times, it gets entrained and trapped in eddy features that last for a few inertial periods. Cyclonic and anticyclonic vorticity maxima are not coincident with regions of enhanced strain, but in filaments, both vorticity and strain are coincident and highly enhanced. Even when the eddies perpetuating mixing are primarily within the mixed layer, the signature of lateral mixing projects into the thermocline beneath.

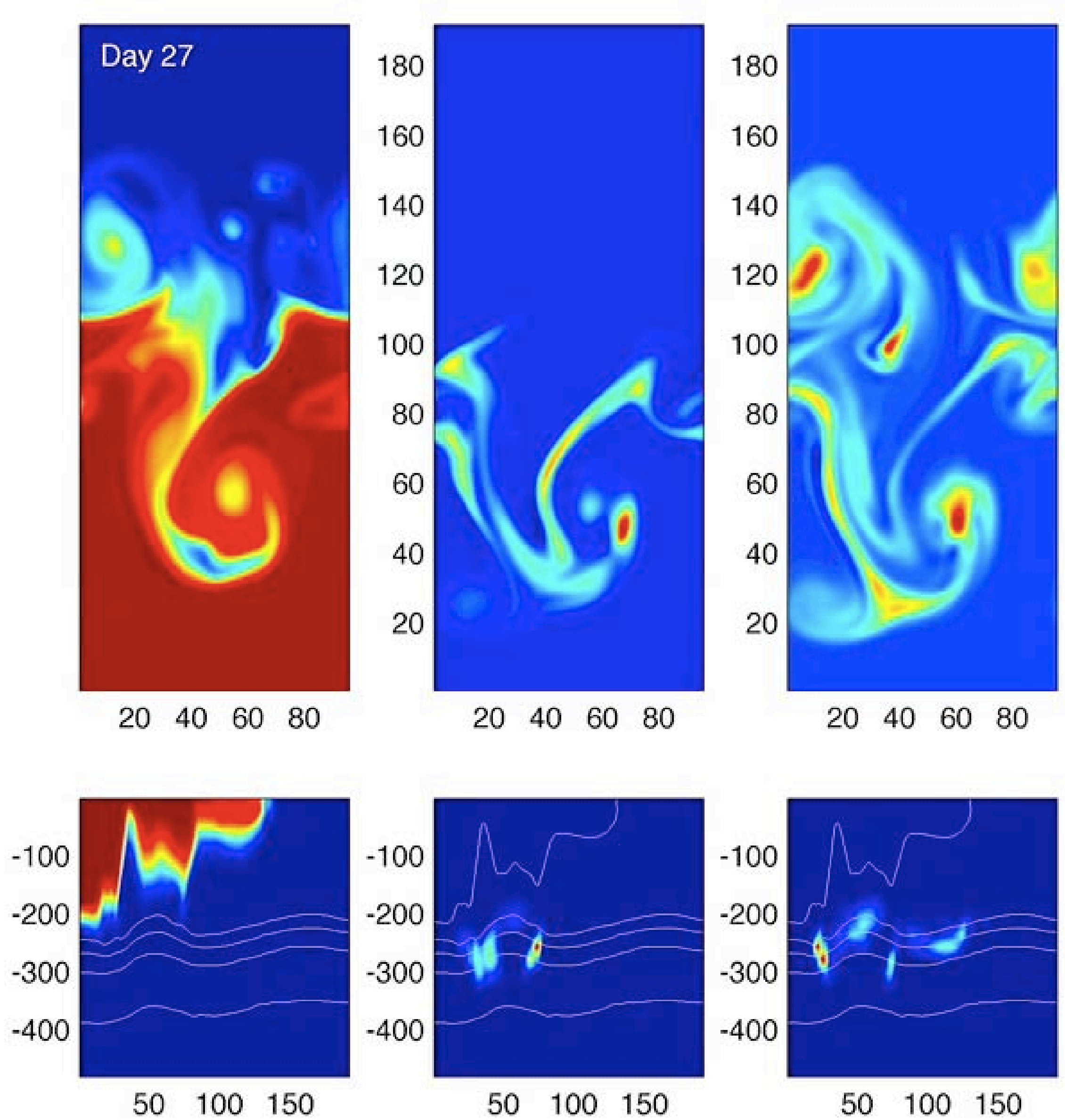

Figure 1. Top row: plan views and lower row: sectional views showing a snapshot in the evolution of 3 tracers. This numerical simulation was to examine frontal mixing by submesoscale eddies. At left: Dye was initialized to be on the warm side of the front as seen in the sectional view. The top left panel shows the formation of a cold filament that extends onto the warm dyed side of the front. The second and third set of panels from left show dye that was released in along-front streaks. At top, we see the stretching and folding of the dye streak, as well as entrapment of dye in eddy like features. At bottom, we see that the dye remains more or less along the same isopycnal surface as it is stirred laterally by eddies in the mixed layer. The mixed layer is made deep (200 m) in these experiments to enhance the mixing. Shallower mixed layers result in the more gradual growth of smaller sized eddies.

The growth in variance of the dye concentration estimated along isopycnal surfaces is more or less linear. But the slope, which denotes the mixing coefficient, changes when the submesoscale eddies

grow to become mesoscale. Since this may be an artifact of the initial condition, we are performing experiments in which we release dye within a spun up eddying field.

In simulations with deeper mixed layers, the scale of submesoscale eddies is larger. This results in a faster increase of tracer variance (Sundermeyer and Ledwell 2001), implying a larger lateral mixing coefficient. Further dye experiments are being carried out for different mixed layer depths and lateral buoyancy gradients.

A significant mechanism for cross-frontal mixing is the generation of filaments that emanate from cusp-like singularities along the front and extend from the cold- to warm-side of the front (e.g. Capet *et al.* 2008). The mixing that ultimately leads to irreversible transfer of tracer across front occurs via an along-axis filamental stretching coupled with a vertical component of strain that causes subduction and annihilation of the filament.

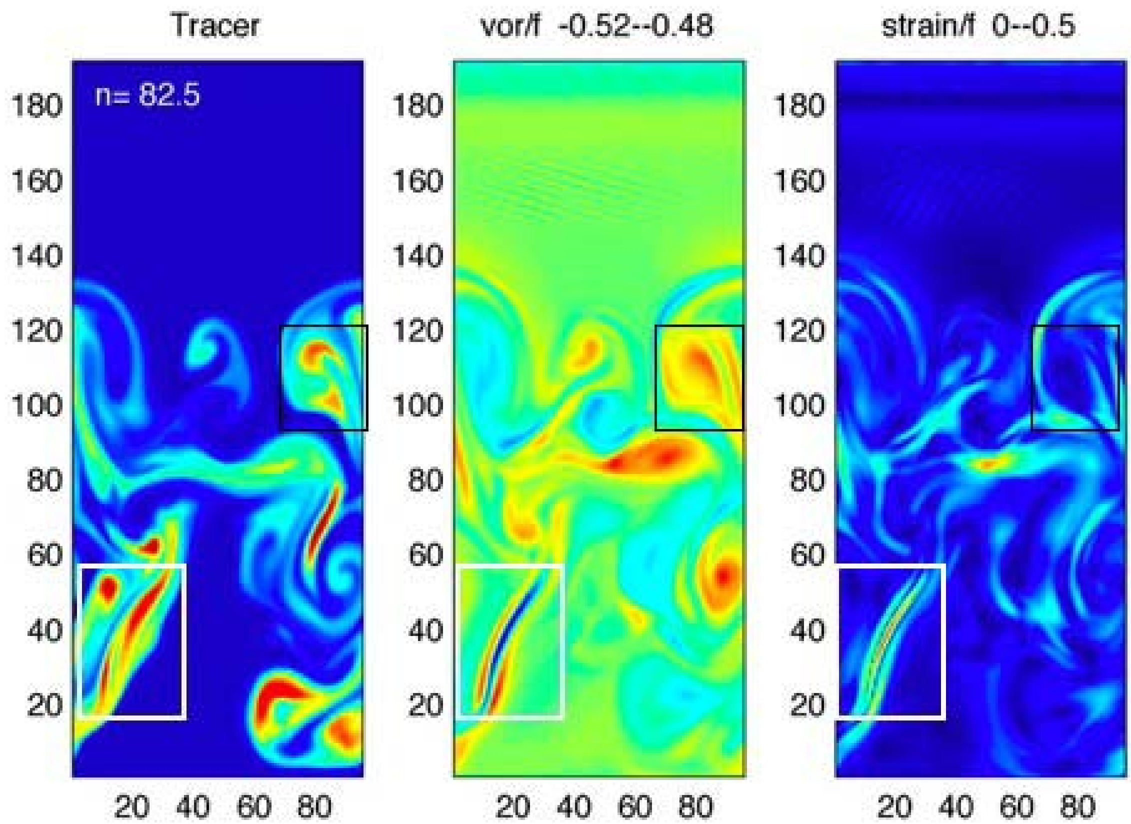

Figure 2. The mixing of a tracer dye streak (left pannel) by submesoscale eddies in a numerical simulation is shown in plan view, alongside the vertical component of the relative vorticity (normalized by f) and the horizontal strain rate (normalized by f). The black rectangle highlights an eddy, which exhibits enhanced vorticity, and minimal strain, which appears large on the perphery of the eddy. The white rectangle highlights a filament, which in contrast shows maximal vorticity (of both signs) and strain rates that are coincident.

RELATED PROJECTS

Mahadevan and Tandon have been recently funded by NSF to characterize the bio-geochemical impacts of submesocale processes and to determine whether submesoscale vertical transport has a greater impact on phytoplankton productivity than mesoscale eddies.

REFERENCES

Capet, X., J.C. McWilliams, M.J. Molemaker, and A.F. Shchepetkin, Mesoscale to Submesoscale Transition in the California Current System. Part II: Frontal Processes. *Journal of Physical Oceanography*, 38, 44–64, 2008.

Fox-Kemper, B., R. Ferrari, and R. W. Hallberg. Parameterization of mixed layer eddies. Part I: Theory and diagnosis. *Journal of Physical Oceanography*, 38, 1145-1165, 2008

Sundermeyer, M. A., J. R. Ledwell, Lateral Dispersion over the Continental Shelf: Analysis of Dye-Release Experiments, *J. Geophys. Res*., 106 (C5), 9,603-9,621, 2001.

Thomas, L. N., A. Tandon, and A. Mahadevan, Submesoscale processes and dynamics. In Hecht, M. and Hasumi, H., editors, *Ocean Modeling in an Eddying Regime*, (AGU Monograph), American Geophysical Union, Washington DC, pages 17-38, 2008.

PUBLICATIONS

Mahadevan, A., A. Tandon and R. Ferrari, Rapid Changes in Mixed Layer Stratification Driven by Submesoscale Instabilities and Winds, Journal of Geophysical Research Oceans 2009, [Accepted September 2009, In Press, Refereed]